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# High power passively mode-locked dissipative soliton fiber laser featuring cladding pumped non-CVD-thulium doped fiber

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The characterization of a thulium-doped fiber made from the new powder technology in the mode-locking regime is reported. High average output power of 185 mW at a repetition rate of 9 MHz was achieved directly from the oscillator, which is resulting in 21 nJ of pulse energy. The single-pulse operation regime was confirmed by careful numerical modeling of the laser cavity.

OCIS Codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers

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## 1. Introduction

Owing to considerable recent progress in different fields of science and technology, high power ultrafast laser sources emitting around 2  $\mu\text{m}$  wavelength range attract an increasing attention. In this context, fiber based systems have asserted their strengths/potential due to noticeable compactness and robustness, while state-of-the-art results in term of absolute values are still lower compared to those obtained from ytterbium doped fiber sources.

Various amplification techniques could be used to achieve either high energy or high peak power at this wavelength. Recently, 100 kW in peak power was obtained [1] with CPA & gain-switched (ns) seed pulse. In turn, mode-locked seed oscillator used in MOPA scheme allows reaching  $\mu\text{J}$ -level in pulse energy with sub-ps pulses [2,3]. Moreover, impressive results were recently demonstrated with CPA systems based on Tm-doped rod-type fibers. Sub-ps pulses were amplified to reach 152 W in average power and 4 MW in peak power [4].

To achieve a high average power directly at the output of the ultrafast oscillator, one must provide effective stretching of the pulse inside the cavity during its round-trip. One of the regimes in which this could be realized, is the so-called dissipative solitonic (DS) regime which demands net normal cavity dispersion. Furthermore, it has been shown that the energy scaling is directly related with absolute value of normal dispersion [5,6]. In contrast to the case of Yb-doped sources, where a fiber chromatic dispersion is naturally normal for  $\lambda > 1.5 \mu\text{m}$ , one must use dispersion compensating elements (either bulk, or specialty fiber based) inside the cavity to provide such an operating regime at 2  $\mu\text{m}$  [7]. Typically, pulse energy measured directly at the output of a passively mode-locked thulium fiber oscillators in net normal dispersion cavities is in order of few mW [8]. Recently, a hundreds-mW average output power level was demonstrated exploiting high-order solitonic concept [9], where even few

nanojoules pulses provided up to 21 kW in peak power due to their sub-ps nature.

In this paper we demonstrated the generation of high average power (185 mW) and high energy (21 nJ) picosecond pulses in the net normal dispersion cavity based on the cladding-pumped Tm-doped fiber fabricated using one of the newest glass manufacturing technologies. This process, called “Repasil”, consisting in the synthesis of doped optical glass by sintering and vitrification of silica powders. Repasil-based fibers have already demonstrated remarkable capabilities for the fabrication of efficient and homogeneous active materials [10], rendering them relevant competitors to existing methods of fiber fabrication. Obtained performances in terms of average and peak powers directly at the oscillator output are not the record ones at this wavelength range; however, to the best of our knowledge, they are the highest in terms of average power and pulse energy directly at the output of the thulium mode-locked fiber lasers with a net *normal* dispersion cavity.

## 2. Fiber preparation and characterization in continuous wave (CW) regime

The material processing for the fabrication of doped silica is based on the REPUSIL process and described in [11]. The active material is made starting from pure silica particles which are doped in an aqueous dispersion with rare earth precursor (0.81 weight %  $\text{Tm}^{3+}$  with ratio  $\text{Al}^{3+} : \text{Tm}^{3+} = 6:1$ ). This synthesis technology allows high batch to batch reproducibility and the silica rods show a high homogeneity: low radial (see Fig 1.a) and longitudinal variation of a refractive index:  $2.10^{-4}$ . It is worth to note that with obtained performances this Repasil technology could be especially useful in fabrication of large cores/volumes and overpasses the limitation of traditional MCVD process on the ability to accurately control the refractive index profile.

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The fabricated fiber has a core diameter equal to 8  $\mu\text{m}$ , an D-shaped outer cladding of  $122 \times 146 \mu\text{m}$ , and is coated with a low index polymer (NA $\sim 0.35$ ) providing an efficient cladding pumping. Its refractive index profile is presented in the Figure 1. The V number is estimated to be 2.36 at  $\lambda = 1900 \text{ nm}$  which confirms that the fiber is truly singlemode in the working region (a near-field image of the fundamental mode at  $\lambda = 1960 \text{ nm}$  is shown in the inset to Fig.1b). The measured cladding absorption reaches 5 dB/m at  $\lambda = 790 \text{ nm}$  while the background losses were estimated to be 0.1 dB/m at  $\lambda = 930 \text{ nm}$  and 0.5 dB/m at  $\lambda = 1335 \text{ nm}$ . It should be noted that the level of grey losses are quite high, compared to MCVD-based fibers, but dissipative solitonic cavity could tolerate them and is an ideal candidate for such a fiber to be implemented in. The performance of the fabricated fiber was tested in a continuous wave regime in a simple 4%-99% laser cavity, giving 43 % of slope efficiency with 5 m long sample.

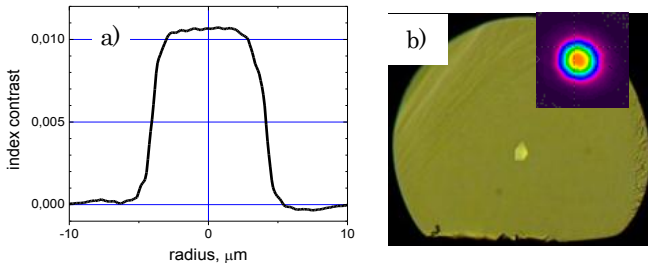


Fig. 1. a) the refractive profile of the fabricated powder thulium-doped fiber, b) corresponding fiber cross-section microscope image, inset – a near-field image of the fundamental mode at  $\lambda = 1960 \text{ nm}$ .

### 3. Experimental set-up

Our oscillator, shown in Figure 2, is based on a Fabry-Perot cavity. To operate in a net normal cavity regime, the dispersion compensation (DC) has been achieved with the help of a commercially available OFS80 fiber, the chromatic dispersion of which is calculated to be  $+0.0489 \text{ ps}^2/\text{m}$  at  $\lambda = 1960 \text{ nm}$ . A small piece of single-mode fiber (SMF-28) has been put in between the Tm-doped fiber and the DC fiber in order to facilitate the splicing and a control of the total cavity dispersion. To evacuate the unabsorbed pump, the end of the active fiber was placed in a high-index polymer. The cavity has been passively mode-locked using a commercially available Saturable Absorber (BATOP-SAM-1960-54). The length of the active Tm-doped fiber (TDF) has been optimized to fit the working wavelength of SA mirror (SAM)  $\lambda = 1960 \text{ nm}$  and estimated to be  $\sim 2 \text{ m}$ .

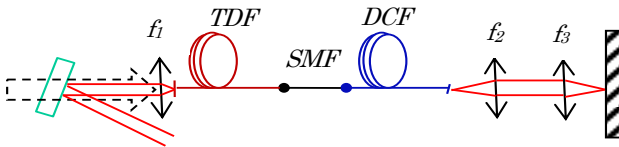


Fig. 2. Principal scheme of the oscillator: TDF – active thulium-doped fiber under test, SMF – transition single-mode fiber (SMF28), DCF – dispersion compensating (OFS80) fiber.

This fiber length still provided efficient laser operation, which was confirmed by the cut-back slope efficiency measurements – drop of only few percents compared to 5 m active fiber sample was observed. The fiber is cladding pumped with a multimode diode operating at  $\lambda = 793 \text{ nm}$  from free-space using a couple of  $f = 8 \text{ mm}$  lenses. The free  $0^\circ$  cleaved fiber-facet acts as output

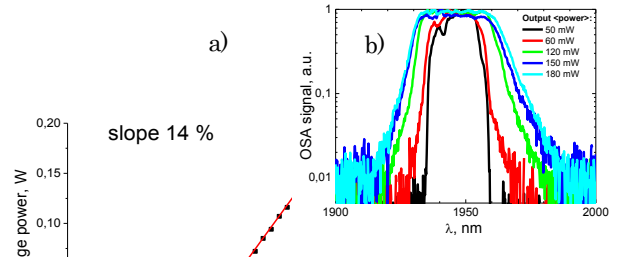


Fig. 3. a) Oscillator efficiency and output average power versus the launched pump power; inset – pulse train, b) spectral evolution with respect to the output average power in the monopulse regime.

coupler. A careful alignment of the focalization on SAM with the pair of  $f_{2,3} = 8 \text{ mm}$  lenses enables a stable self-starting mode-locking.

### 4. Experimental results

Up to 185 mW ( $f = 9 \text{ MHz}$ ,  $E_p \sim 21 \text{ nJ}$ ) of average power was obtained at the output of the oscillator in the single-pulse regime (see fig. 3a). Further increase of the pump power led to the doubled or even tripled pulse operation with respect to the fundamental frequency. We address this issue to the excessive energy fluence incident on SAM. Spectrums at different output average powers are presented in figure 3b. The full width at half maximum (FWHM) varied from 16.6 nm up to 34 nm at maximum signal power level.

The temporal characterization with 85 ps range autocorrelator (Femtochrome FR-103-XL) showed no additional replicas when pump power lies in the single-pulse region (up to 185 mW) (see Fig. 4). A typical autocorrelation trace for the output power  $P_s = 50 \text{ mW}$  ( $E_p \sim 5.6 \text{ nJ}$ ), which lies in the beginning of the monopulse region, is presented in Fig. 3a. The autocorrelation FWHM (corresponding spectrum FWHM = 16.6 nm) was measured to be 24.4 ps which gives 15.8 ps of pulse duration (supposing  $\text{sech}^2$  pulse shape).

### 5. Pulse compression experiment

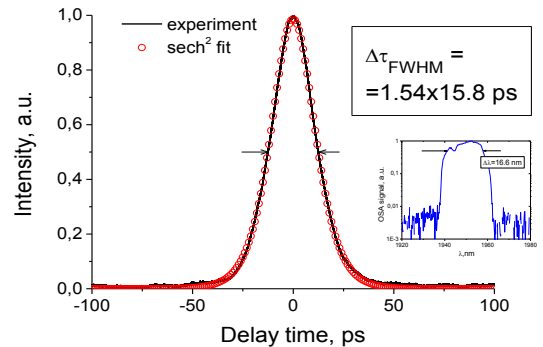


Fig. 4. The autocorrelation trace and corresponding spectrum (in the inset) at the output average power  $P_s = 50 \text{ mW}$

Afterwards, a pulse compression experiment was conducted using a pair of 600 l/mm diffraction gratings with a blaze wavelength of 1.6  $\mu\text{m}$ . However, at  $\lambda = 1.95 \mu\text{m}$  these gratings become efficient only for one polarization with diffraction

efficiency of 90%. Therefore a Glanpolarizer and two half-wave plates were used to maximize a) the average power of the pulse in the compressor and b) the signal in the autocorrelator (AC) (see Fig.5). It is worth to note that the polarizer also acts as the optical isolator preventing from the parasitic back reflections to the oscillator cavity that could easily disturb the mode-locking regime. Due to the mentioned limitations the overall compression efficiency in this configuration was not exceeding 33 %.

At the maximum output average power, however, the Glan polarizer did not provide a high optical isolation and the mode-locking regime was disturbed after few minutes of operation. Therefore the average output power providing unperturbed regime was fixed to be 100 mW ( $E_p = 11 \text{ nJ}$ ) that gave an output pulse spectrum FWHM of 22.6 nm (see Fig. 6a). The corresponding autocorrelation traces for the pulse before and after compression are presented in Fig. 6 (b and c, respectively). The 11.5 ps pulse was compressed down to 1.9 ps (assuming  $\text{sech}^2$  profile,  $P_{\text{peak}} = 1.9 \text{ kW}$ ). A time-bandwidth product for the compressed pulse is equal to 2 that is approximately 2.5 times higher than typical values ( $\sim 0.8$ ) for dissipative solitonic regime.

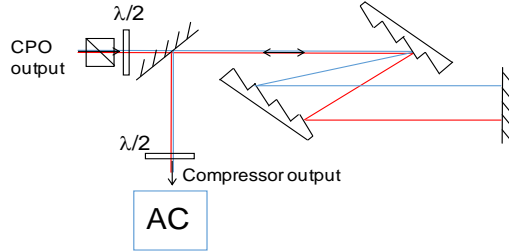


Fig.5. Pulse compression set-up. AC – autocorrelator.

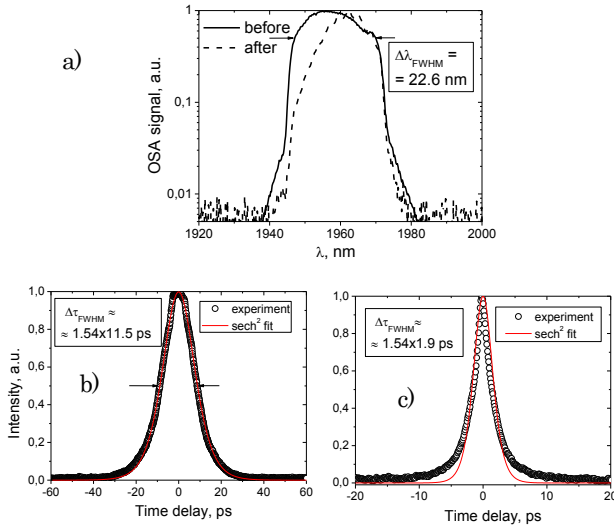


Fig.6. Compression experiment: spectrums and autocorrelation traces of the pulse *before* (a-solid line, b) and *after* (a-dashed line, c) compression. In Fig. 6b,c the solid red line represents  $\text{sech}^2$  fit to the experimental data.

This could be explained by not optimal alignment of diffraction gratings in our set-up (one could see a slight cut of the short wavelengths components in compressed pulse spectrum, Fig 6a). One could mention also, that more efficient gratings (etc, working in transmission, polarization independent) together with a better

compressor alignment immediately allows to reach 10 kW peak power level in this system.

## 5. Numerical modeling

To confirm the monopulse operation, a numerical modeling was made with the help of a commercially available software [12] based on the split step Fourier method. The scheme used in the calculations is illustrated in Fig. 7. The elements lengths ( $L$ ) were taken to fit the experimental cavity:  $L_{\text{TDF}} = 1.9 \text{ m}$ ,  $L_{\text{OFS80}} = 7 \text{ m}$ ,  $L_{\text{SMF28}} = 2.1 \text{ m}$ ,  $L_{\text{free-space}} = 0.4 \text{ m}$ . The SAM parameters were chosen respecting the datasheet: a relaxation time of  $\tau = 10 \text{ ps}$  and a modulation depth of  $\Delta R = 30 \%$ . The dispersion parameter of SMF28 fiber is known to be  $\beta_{2,\text{SMF}} = -0.0679 \text{ ps}^2/\text{m}$  at  $1.9 \mu\text{m}$  [8],



Fig.7. Configuration of the element blocks used in the numerical modeling of the experimental cavity from Fig.2. Dashed lines with arrows illustrate cavity round trip. OC – output coupler element

which corresponds to  $-0.0778 \text{ ps}^2/\text{m}$  at  $1.96 \mu\text{m}$ . For TDF the dispersion was estimated to be  $\beta_{2,\text{TDF}} = -0.07875 \text{ ps}^2/\text{m}$  at  $1.96 \mu\text{m}$ . Thus the cavity has a moderate level of the net normal dispersion  $\beta_{2,\text{net}} = +0.0586 \text{ ps}^2$ . The Fresnel 4% reflection at the fiber end-facet provided the positive feedback in the laser cavity. The gain FWHM was measured to be  $\Delta\lambda = 160 \text{ nm}$  and assumed to have a Gaussian shape.

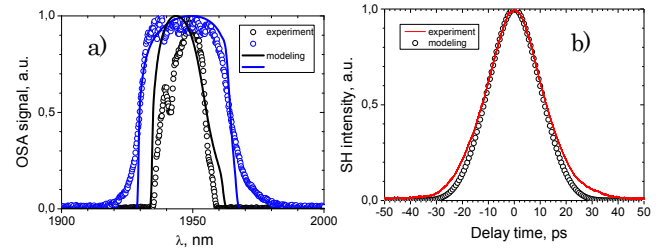


Fig.8. Experimental (open circles) and corresponded calculated (solid lines) of a) spectra and b) autocorrelation traces for monopulse ML regime. a) Black color for lower and Blue color for upper ML thresholds, respectively, b) for lower ML threshold

The modelling process initiated by the “quantum-noise” allowed us to identify the region of the monopulse operation of the oscillator. This is illustrated in Fig.8 where a comparison between the experimental and theoretical spectra as well as the corresponding autocorrelation traces are presented for minimum and maximum pump power providing monopulse operation. It is worth to note that the spectral & temporal characteristics in this range are matching quite well with that observed in the experiment. The gain saturation energy  $E_{\text{sat}}$  was varied in the range between 0.1 and 0.4 nJ. With further increasing of  $E_{\text{sat}}$  (which is, in turn, proportional to the pump power) converging to the stable solution was not possible.

## 6. Conclusion

In conclusion, we presented a detailed characterization of a fiber made from a novel powder technology in the mode-locking regime

initiated by a commercially available saturable absorber. The stable self-starting operation regime could be preserved during hours when proper alignment is achieved. In terms of performance we demonstrated up to the 185 mW of average power (14 % slope efficiency, pulse energy  $E_p = 21$  nJ) in single pulsed regime, confirmed by the theoretical modelling of the cavity. However, an improper isolation at the laser output allows the hours-long operation of the laser at the power level less than 100 mW only and pure single-pulse regime in not stable region, still needs to be confirmed experimentally in stabilized system. Precise measurements of the pulse duration were done at 50 mW of output average power ( $E_p = 5.6$  nJ) for uncompressed pulses in the beginning of the single-pulse regime region and at 100 mW ( $E_p = 11$  nJ) of average power during the compression experiment. The 11.5 ps pulses were compressed down to 1.9 ps corresponding to a peak power  $P_{\text{peak}} = 1.9$  kW. The bulk compression scheme did not allow increasing the peak power in compressed pulse due to the low optical efficiency of diffraction gratings available in the experiment.

The presented results confirm the interest of such kind of fibers to be implemented in potentially all-fiber schemes for operation in mode-locking regimes. Moreover, relatively high (185 mW) average power output directly at the output of the oscillator was demonstrated at wavelength of 1.96  $\mu\text{m}$ .

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